Renewable and Sustainable Energy Reviews 21 (2013) 456–468

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Progress and recent trends of wind energy technology

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ARTICLE INFO

Article history:
Received 8 October 2012
Received in revised form
3 January 2013
Accepted 4 January 2013
Available online 9 February 2013

Keywords:
Wind energy
Fish schooling concept
VAWT
Energy storage system
Technological life cycle

ABSTRACT

In this paper, along with the progress of modern wind energy technology, the trends of wind energy technology and potential challenges have been studied thoroughly. It is estimated that within the next 2–3 decades, the Vertical Axis Wind Turbine (VAWT) can dominate the wind-energy technology. The VAWT requires less land space and using the same space; it is capable of producing more wind energy than that of its counterpart. By implying the Fish Schooling Concept effectively and successfully, it is possible to advance the wind-energy technology more. In the last 3–4 decades, the wind turbine capacity has been increased around 30–40 times. With the increase of wind energy capacity, the demand of the energy storage system has been increased significantly. Along with the many energy storage systems, fuel cells and batteries are the two most promising devices to meet the demand in RE systems. The wind-energy technology is established itself but not yet fully mature and hence there are many areas where improvements are required to reduce the cost of wind energy.

Contents

1. Introduction

Energy is one of the inseparable particulars that governs our lives and promotes civilization. The social and economic health of the modern world depends on sustainable supply of energy in most of

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.01.007

the cases. However, intensive and uncontrollable developments of human civilization and industrialization have a great negative impact on the environment as well as on energy resources. In order to prevent further depletion of natural resources and degradation of our environment, the future technologies must include sustainable development principles and criteria implementation in technical processing, products and operations [1–5].

According to the IEA's Energy Technology perspective (ETP) publication estimation, the emissions of greenhouse gases from the energy sector will be increased by 130% over 2005 levels, by 2050, without the implication of new technologies [6–9]. To get rid of the GHGs emissions, an energy technology revolution will be required including the greater energy efficiency, renewable energy, nuclear power and decarburization of fossil-fuel based power generation. The ETP BLUE map scenario shows that the wind power could contribute 12% of the necessary reductions from the power sector [10]. Fig. 1 shows the contribution of CO_2 reductions for the different energy sectors. In addition to the CO_2 benefit of wind power, the emissions of pollutants like oxides of sulfur and nitrogen can also be reduced by wind energy technology [9,11–14]. Like other power technologies of RE resources, wind energy is widely available throughout the world and can contribute to reduce energy import dependence. Nowadays, the extensive use of fresh water in cooling purpose at the thermal power plant is causing a serious concern in dry regions. In comparison with the thermal power plant, the wind farm consumes a very low amount of water. Fresh water problem becomes an important issue in some countries like China, India, USA, etc. [15–20].

Due to the modern technological developments, the wind power has achieved remarkable advances. Since 1980, advances in aerodynamics, structural dynamics and micrometeorology have contributed to a 5% annual increase in the energy production of the turbines [21,22]. Along with the enormous increase of energy output for turbines, the weights of the turbines and the noise they emit have been halved over the last few years. It is possible to generate more power from wind energy by selecting the wind farm site with a suitable wind electric generator, using high-capacity machine and faster computer-based machining technique, increasing power factor and better policies from governments [12,23–25]. Among other applications of renewable-energy technologies, wind power generation has an edge due to its technological maturity, good infrastructure and relatively competitive cost. At good windy sites, the wind power is already competitive with that of the traditional fossil-fuel generation technologies. As the wind-energy technology improvement is going on, the experts predict that the wind power would capture 5% of the world energy market by the year 2020. Advanced wind turbine technology must be more efficient, more robust and less costly than current turbines technology [26–28].

In this article, the progress and trend of the main wind energy technology (Wind Turbine) have been discussed thoroughly. The Fish Schooling Concept for VAWTs and its benefit over the HAWTs have been exemplified. Along with this, the very useful appurtenance like energy storage system has been discussed briefly. Though several works have been done on the wind-energy policy,

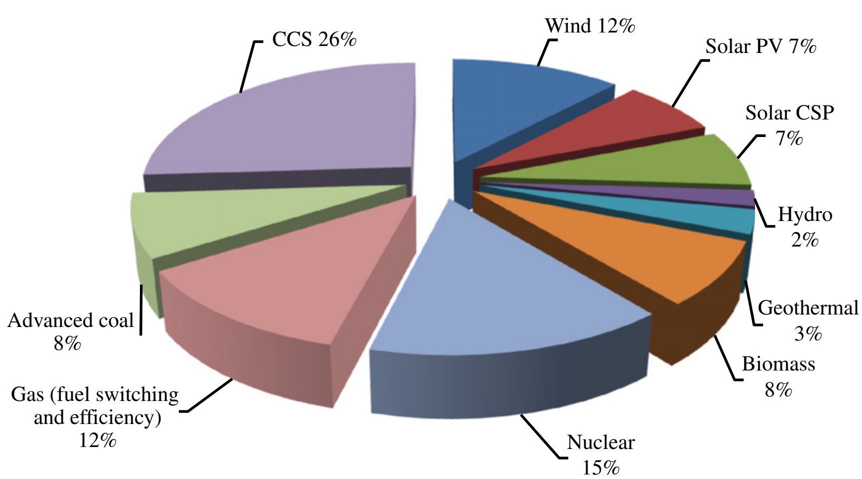

Fig. 1. Contribution of CO_2 emissions reductions in various power sectors [10].

Table 1
Installed capacity (MW) of top 10 wind power generating countries [42].

Nation	2005	2006	2007	2008	2009	2010	2011
China	1266	2599	5912	12,210	25,104	44,733	62,733
USA	9149	11,603	16,819	25,170	35,159	40,200	46,919
Germany	18,428	20,622	22,247	23,903	25,777	27,214	29,060
Spain	10,028	11,630	15,145	16,740	19,149	20,676	21,674
India	4430	6270	7850	9587	10,925	13,064	16,084
France	779	1589	2477	3426	4410	5660	6800
Italy	1718	2123	2726	3537	4850	5797	6747
UK	1353	1963	2389	3288	4070	5203	6540
Canada	683	1460	1846	2369	3319	4008	5265
Portugal	1022	1716	2130	2862	3535	3702	4083
Rest of world	10,168	12,576	14,386	18,096	21,601	27,380	32,446
Total	59,024	74,151	93,927	121,188	157,899	197,637	238,351

development, status and technology, offshore wind energy technology, etc. [29–41], no work has been done on the progress and recent trends of wind energy technology. It is expected that this study will be very useful for the researchers as well as the professionals in the wind energy field.

2. Global scenario of wind energy

From Table 1, it is seen that the global wind power installed 238,351 MW in the year 2011, an increase in total installed generating capacity of nearly 75% over the period of 2005–2011. Among the top 10 wind power countries in the world, the highest developing country is China with the installed capacity of 62,733 MW at the end of 2011, around 98% growth over the period of 2005–2011. The next highest wind power developed countries are France, Canada, USA and UK with the growth rate of around 88%, 87%, 80% and 79% respectively from the year 2005 to 2011. However from Fig. 2, it is found that at the end of 1996, the cumulative wind power installed capacity was only 6.1 MW and at the end of 2004 the installed wind power capacity was 47.6 MW.

Based upon the World Wind Energy Report in 2011 (Fig. 2), the following global wind energy summary can be drawn [42,43]:

- In 2011, the worldwide wind energy capacity reached 238,351 MW, out of which 40,714 MW was added from 2010 to 2011, slightly greater than 2009–2010.
- All the wind turbines installed worldwide by the end of 2010 can generate 430 TWh per annum which is equal to 2.5% of the global electricity consumption.
- China overcome the USA in total wind power installed capacity and added around 18,928 MW within 1 year, accounting for more than 50% of the world market of new wind turbines.
- Germany keeps its number one position in Europe with the wind installed capacity of 27,215 MW, followed by Spain with less than 6539 MW.
- Asia accounted for the largest share of new wind turbine installations around 54.6% whereas Europe stay at the 2nd position with the installations of around 27%.
- WWEA estimated that a global capacity of 600,000 MW is possible by the year 2015 and if the growth is continued in the same trend then more than 1,500,000 MW can be achieved by the year 2020.

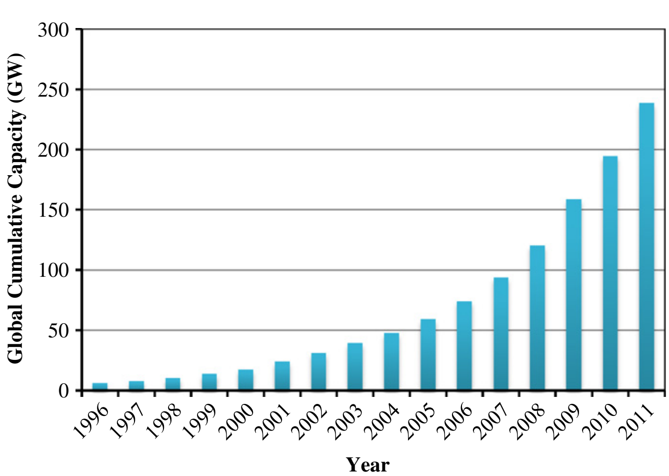

Fig. 2. Global wind power cumulative capacity [44].

3. Wind turbines

Wind turbine, which is of mainly horizontal axis type and vertical axis type, can convert wind energy into mechanical energy. Although the Horizontal Axis Wind Turbine (HAWT) is a common type, the Vertical Axis Wind Turbine (VAWT) is valued increasingly in the world, especially the straight bladed VAWT because of its advantages such as low cost, easy installation and maintenance and so on [45,46]. Based on the working function of the wind-energy conversion system, it can also be divided into those which depend on aerodynamic drag and aerodynamic lift. The drag principle was used by the early Persian VAWT wheels that have a very low power coefficient, with a CP, max of around 0.16 only. However, the modern wind turbines are predominantly based on the aerodynamic lift [47–54]. The comparison between HAWT and VAWT and relatively their advantages and disadvantages have been given in Table 2.

3.1. Modern wind turbine technology and challenges

Since the commercialization of wind turbine technology in the early 1980s, many developments have taken place but the architecture of the mainstream design has changed very little. In the modern HAWT, the wind energy is extracted by means of a horizontal rotor, upwind of the tower, with three blades that can be pitched to control the rotational speed of a linked shaft. The three-bladed rotor proliferates and typically has a separate front bearing, with low speed shaft connected to a gearbox that provides an output speed suitable for the most popular four-pole or two-pole generators. In a VAWT, the shaft is mounted on a vertical axis, perpendicular to the ground. VAWTs are always aligned with the wind. Fig. 3 shows both the modern HAWT and VAWT. However, the big challenge for the modern wind industry is to design the efficient wind turbine to harness the wind energy and turn it into electricity [57–62]. In the last 30 years, the size of the wind turbines have increased by a factor of 100 while the cost of energy has reduced by a factor of more than 5, and the industry has moved from an idealistic fringe activity to the power generation industry. At the same time, the engineering base and computational tools have developed to match with the machine size and volume. Up to this time, this is a remarkable story of wind turbine; however it is far from finished line; many technical challenges remain and even more spectacular achievements will be followed [61,63,64]. Some of the important features of wind turbine will be discussed hereafter.

3.1.1. Number of blades

The determination of the number of blades involves design considerations of aerodynamic efficiency, component costs, system reliability and esthetics. In the 1980s and early 1990s, attempts are made to commercialize one and two bladed wind turbine design; however, most of the modern wind turbines have three blades. The single bladed design is the most structurally efficient for the rotor blade as it has the greatest blade section dimensions with all the installed blade surface area in a single beam [66,67]. However, with a counterweight to balance the rotor statically, efficiency is reduced and complex dynamics is required for a blade hinge to relieve loads. Aerodynamic efficiency increases with the increase of the number of blades but diminishes return. Increasing the number of blades from one to two yields a 6% increase in aerodynamic efficiency, while increasing from two to three yields only an additional 3% efficiency [68]. The decisive factor in eliminating one and two bladed wind turbine from the commercial market has been the visual impact. Like many design considerations, the number of blades on a wind turbine is a compromise. Three blades give a good compromise, not too much air disturbance for the following blade, and a reasonable amount of

energy gathered from the airflow and delivered to the electrical generator atop the mast [69–72].

3.1.2. Power control: pitch versus stall

The main function of the wind-turbine design is to produce electrical energy as cheaply as possible. Therefore, wind turbines are designed to extract maximum energy from wind and yield the maximum output power. However, whenever a wind turbine is designed, it does not consider the power output at strong wind because such strong winds are very rare. To avoid the damage to wind turbine during strong wind, it is required to waste part of the excess energy of the wind. So, all the wind turbines used some sort of power control [73,74]. The modern wind turbine mainly used two types of power controlling system. First, the pitch controlling wind turbine where the electronic controller checks the power output of the turbine several times in each second. When the power output of the turbine is too high, the controlling system sends the signal to the blade pitch mechanism that immediately turns the rotor slightly out of wind. Conversely, whenever the wind force becomes low, the rotor gets back to its original position. Secondly, stall-regulated wind turbine requires a speed regulation and a suitable torque speed characteristic intrinsic in the aerodynamic design of the rotor. The geometry of the rotor blade of stall controlled wind turbine has been designed to ensure that the moment the wind speed becomes too high, it creates turbulence on the side of the rotor blade which is not facing the strong wind. The stall prevents the lifting force of the rotor blade from acting on the rotor [75–80]. The main features of these two systems are shown in Table 3.

Table 3
Main features of stall and pitch controlling system [81].

Stall	Pitch
Fixed blade pitch	Blade pitch activated by wind turbine control
Passive power control by stall effect	Active power control
Control parameter: wind speed	Control parameter: power output, wind speed and rotor speed

3.1.3. Development trend of WTs and wind turbine size

The history of wind power shows a general evolution from the use of simple, light devices driven by aerodynamic drag forces, to heavy, material-intensive drag devices, to the increased use of light,

Table 2
Comparative study of HAWT and VAWT [55,56].

Nos	HAWT	VAWT
01	Rotating axis of the wind turbine remains horizontal, or parallel with the ground	Rotating axis remains vertical, or perpendicular to the ground
02	It is able to produce more electricity from a given amount of wind	It produces up to 50% more electricity on an annual basis versus conventional turbines with the same swept area
03	It is suitable for big wind application	It is suitable for small wind projects and residential applications
04	Comparatively heavier and not suitable for turbulent winds	Lighter and produce well in tumultuous wind conditions
05	HAWT only are powered with the wind of specific direction	Vertical axis turbines are powered by wind coming from all 360°, and even turbines are powered when the wind blows from top to bottom
06	Not suitable to generate electricity from the wind speed below 6 m/s and generally cut out speed 25 m/s	Generates electricity in winds as low as 2 m/s and continues to generate power in wind speeds up to 65 m/s based on the model
07	They cannot withstand extreme weather conditions due to frost, freezing rain or heavy snow plus heavy winds in excess of 50 m/s	Withstands extreme weather such as frost, ice, sand, salt, humidity, and very high wind conditions in excess of 60 m/s
08	Birds are injured or killed by the propellers since they are not solid objects so the birds fly into the blades	Does not harm wildlife as birds can detect a solid object and can be seen on aircraft radar
09	Most are self-starting	Low starting torque and may require energy to start turning
10	Difficult to transport and install	Lower construction and transportation costs

Fig. 3. Horizontal and vertical axis wind turbine [65].

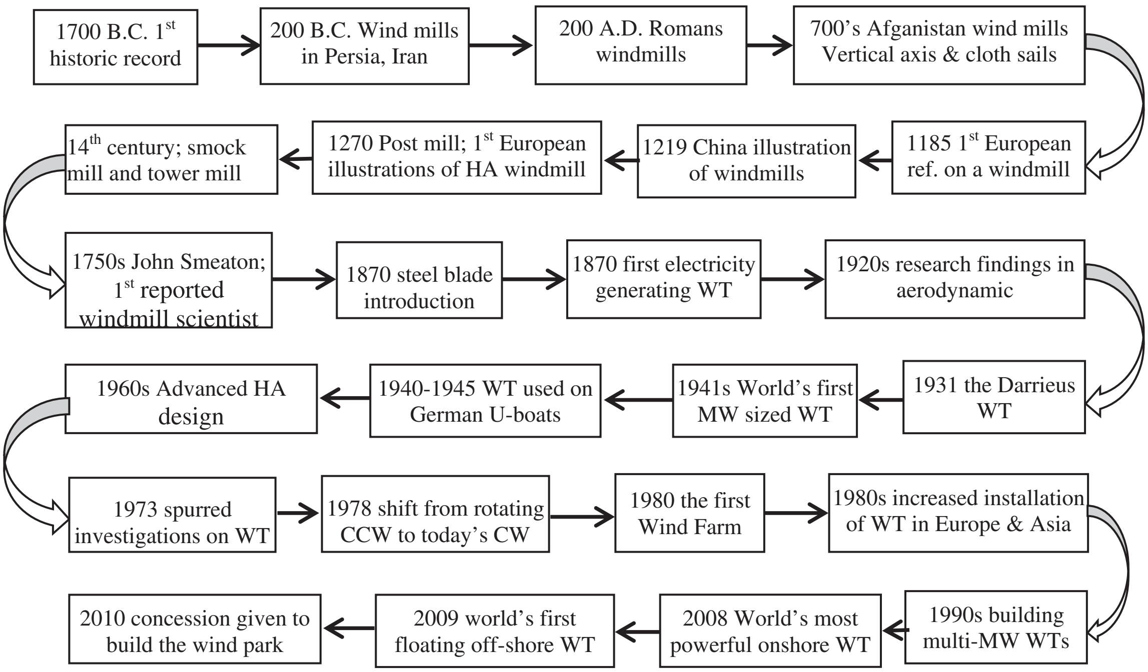

Fig. 4. Historical development trend of WTs [90,91].

material-efficient aerodynamic lift devices in the modern era. The historical development trend has been shown in Fig. 4. In the 1980s, manufacture of commercial wind turbines was started with Danish technology. From 20–60 kW capacity with rotor diameters of around 20 m, wind turbine size has been increased to 2 MW and above [11,40]. The improvement of the wind turbine has been continued in the sense to capture as much energy as possible from the wind [82,83]. Fig. 5 shows the history of the growth of the HAWT size and auspicate a few concepts for the future wind turbine size. In the last decade, the wind turbine size has been increased significantly. In 2005, the size of the most common wind turbine size was around 750 kW and only 21.5% of the newly installed capacity wind turbine was MW-class. Since then some companies like Dong Fang and Gold Wind have produced the MW-level wind turbine, and the capacity increased from 600 kW to 1 MW or above. In 2010, the MW-level wind turbine has occupied around 86.8% of the market share [84–89].

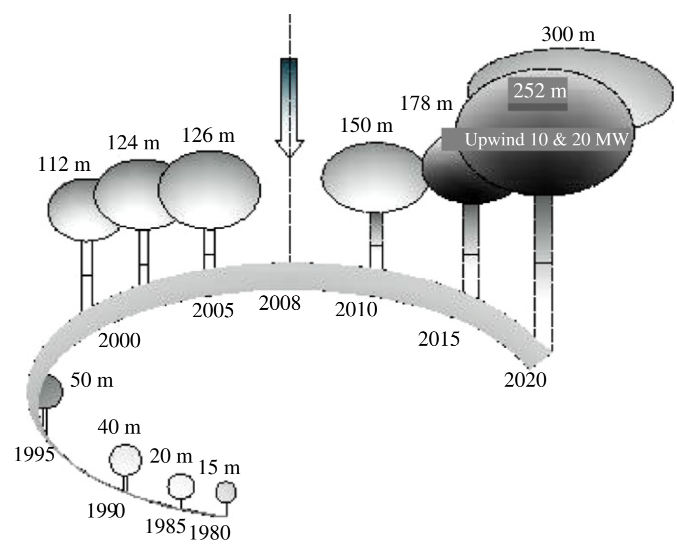

Fig. 5. Growth in size of commercial HAWT [87].

4. Recent trends of wind turbine technology and its effectivity

In the modern wind turbine technology, the HAWTs are highly developed and currently available in the entire existing wind farm. On the other hand, the VAWT in the present wind farm is very rare, and the majority of the research on its design was carried out in the late 1970s and early 1980s at the US Department of Energy Sandia National Lab and in the UK by Reading University and Sir Robert McAlpine and Sons Ltd. [92–96]. However, when it was proven that HAWTs are more efficient for large-scale wind energy production, interest in VAWT design was lost and after that a very little research on VAWT has been carried out [97–101].

The technical development of VAWTs lags significantly behind that of HAWTs, though VAWTs are aerodynamically more efficient than HAWTs. Moreover, it has been suggested that VAWTs are more appropriate in large scale (10 MW+) wind energy generation [102,103]. Very recently there has been a revivification regarding VAWTs and many researches have been carried out due to its aerodynamic efficiency and performance regarding flow separation and alleviating adverse effects on energy production [50,104–106]. It is observed that wind is always changing its speed, and direction is rarely uniform. VAWTs do not need any unidirectional wind speed to produce electricity from wind as its counterpart HAWTs very much needed. In other words, VAWTs are omnidirectional that negates the need for a yawing mechanism. Therefore, VAWTS can be more effective in the complex urban terrains to harness the wind energy that helps to increase the capacity of small-scale wind power generation [107–109].

4.1. *The Fish Schooling Concept for VAWT*

The first scientific studies dealing with schools were carried out upon an average of small-scale groups, only with some individuals or at most 10 subjects, inside several aquariums or ponds. Despite their limits, those works allowed to establish basic rules concerning gregarious behavior [110]. To sum up, a definition given by Soria and Dagorn [111], "a school of fish can be described as a provisional group of individuals, generally from the same species, the same size

and within the same biological cycle, united by a mutual attraction, and showing different degrees of coordination of their swim ability within a centred group. They maintain constant contact, mostly visual, but by acoustics and olfactory means as well. These individuals can, at any time, come to an organized action that uses the same biological skills for any member of the group. It is observed a synchronisation of individual movement inside the school."

4.2. Relationship between the Fish-Schooling Concept and VAWTs farm

Though most of the wind farms in the modern era consist of HAWTs due to its dominancy over the VAWTs, it is found that in the VAWTs farm, the rotations of the turbines are in the same direction. As a fish swims, it sheds vortices from its tail into its wake. It has been previously proposed that schooling fish takes advantage of these shed vortices, thereby minimizing the energy required for locomotion [112,113]. However, during the study of vortices created by the fish, Dabiri [114] found that the rotations of some vortices are in the clockwise direction while some vortices are in the anticlockwise direction of the same fish. He also noticed the constructive hydrodynamic interference between the wakes of the neighboring fish which can be applied to VAWTs to enhance the efficiency. With the optimal placement, according to Dabiri, it is possible to get 10 times more energy out from the same wind farm using VAWTs instead of HAWTs. Further study on VAWTs farm by Whittlesey et al. [115] suggested that substantial benefits can be achieved by placing VAWTs in a strategic array as a result of the relationship among the turbines. Fig. 6 shows the relationship between the Fish Schooling Concept and the VAWTs farm where at the left side, the vortices left behind by the fish are seen and at the right side, the configurations of VAWTs are shown.

4.3. Comparison between HAWT and VAWT with respect to footprint

The main problem in the Renewable Energy (RE) is that its sources are more diffuse than fossil fuel; hence the present technologies of RE require substantial space to extract the energy in an economical way. For wind energy, this problem is more acute than any other RE. Modern wind farms consist of HAWTs that require significant space to separate each wind turbine from the adjacent ones. This aerodynamic constraint limits the amount of power that can be extracted from a given wind farm footprint (the estimated land area requirements for wind power systems). The footprint, which is typically around 0.25 acres per turbine, does not include the 5–10 turbine diameters of spacing required between wind turbines. This requirement obliged the wind farm away from the highly demandable energy sites to the remote sites and increased the cost of energy by adding grid systems [116–118]. To achieve 90% efficiency from HAWTs, turbines must have 3–5 turbine diameters and 6–10 turbine diameter space in the cross-wind and downwind direction respectively in the wind farm. The maximum power density that can be achieved from such a type of wind farm is only 2–3 W/m^2 whereas for VAWTs farm it can be several times, which is shown in Table 4 from the computer modeling results [119].

The power density of VAWTs is higher than that of HAWTs because the swept area of the rotor need not be equally distributed between their breadth—which determines the size of its footprint and its height. On the other hand, the breadth and height of the rotor swept area are identical for the case of HAWTs. Therefore, it is very easy to increase the swept area of VAWT without increasing the footprint whereas in case of HAWT both are necessarily increased. Fig. 7 shows the comparative swept area of the rotor of HAWT and VAWT.

Table 4
HAWT and VAWT power density comparison [114].

WT	Rotor diameter (m)	Rated power (MW)	Power density (W/m^2)
HAWT	112	3.0	304
HAWT	100	2.5	318
VAWT	1.2	0.0012	1061

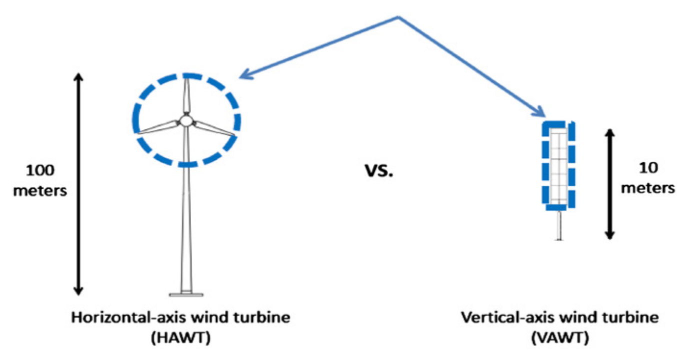

Fig. 7. Wind energy flux swept area of HAWT vs. VAWT [120].

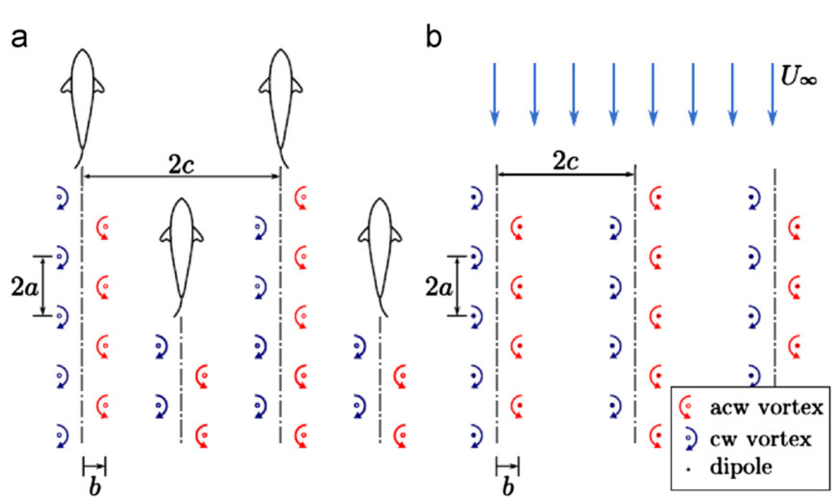

Fig. 6. Inter relationship between the shed vortices from schooling fish and arrangement of VAWTs in the wind farm [113].

5. Batteries as a recently developed energy storage technology

Introducing an energy storage element in connection to a wind power plant changes the spectrum and statistical distribution of the output power. By increasing the amount of storage systems to the wind power plant, the output of wind farm has become more controllable and predictable [121–123]. Due to the stochastic nature of wind, electric power generated by wind turbines is highly erratic and may affect both the power quality and the planning of power systems [124]. Therefore, energy storage and conversion have become a prime area of research to address both the societal concerns regarding the environment and pragmatic applications such as the powering of an ever increasing cadre of portable electronic devices [125–128]. Storage system will have to play an important role in the wind power plant by controlling wind power output that enables the increased penetration of wind power in the grid system [129–131].

A variety of storage technologies are available for storage of energy in the power system. Recently the electrical energy storage technologies include the following types of storage media [132]:

- Batteries
- Flow batteries
- Fuel cells
- Flywheels
- Superconducting magnetic energy storage (SMES)
- Super capacitors
- Compressed air energy storage (CAES)
- Pumped hydro

However, by considering all aspects along with flywheel, fuel cells and batteries are the two most impacting energy storage devices in the RE systems. Batteries take in electricity from another producing source, convert the electricity to chemical energy, and store it as a liquid of solution. When operators need energy from the battery, an electric charge chemically converts the energy back into electrons, which then move back into a power line on the electric grid. There are several promising battery technologies for grid energy application including advanced lead-acid, nickel cadmium (NiCd), nickel metal hydride (NiMH), lithium ion (Li-ion), sodium–sulfur (NaS) and flow batteries [132–134]. Several of them are briefly discussed in the following.

5.1. Advanced lead-acid

Lead acid batteries are a mature and proven technology in use in a number of applications including frequency regulation, bulk energy storage for variable RE integration, and distributed energy storage systems. However, the technology development of lead-acid battery technology is going on. During discharge in a traditional lead-acid battery, sulfuric acid reacts with the lead anode (positive electrode) and cathode (negative electrode) to create lead sulfate. The process reverses during charge. Researchers have found that adding carbon to the battery seems to minimize or prevent the detrimental crystallization from occurring, thus improving the life cycle and overall lifespan of the battery.

5.2. Sodium–sulfur (NaS)

The sodium–sulfur battery uses sulfur combined with sodium to reversibly charge and discharge, using sodium ions layered in aluminum oxide within the battery's core. The battery shows potential to store lots of energy in small space. In addition, its high energy density and rapid rate of charge and discharge make it an attractive candidate for applications that require short, potent bursts of energy. Sodium–Sulfur batteries are a commercial energy storage technology with applications in electric utility distribution grid support, wind power integration, and high-value electricity services.

5.3. Lithium ion (Li-ion)

In a lithium-ion battery cell, positively charged lithium ions migrate through a liquid electrolyte (fluids that conduct electricity) while electrons flow through an external circuit. Both move back and forth from one side to the other. This movement creates and stores energy. Li-ion batteries store energy in various components, composed of layers of different elements, such as lithium, manganese and cobalt. Currently, the lithium-ion batteries have been used significantly in the portable electronics and medical devices [133]; however, their use in the automotive and RE storage applications is of quite potential in the near future. Li-ion batteries achieve energy storage efficiency of almost 100% and have the highest energy density [135].

5.4. Flow batteries

A flow battery is a type of rechargeable battery that stores electrical energy in two tanks of electrolytes. When operators need energy, they pump liquid from one tank to another. During this slow and steady process, the technology converts the chemical energy from the electrolyte to electrical energy. When operators need to store energy, they reverse the process. The size of the tank and the amount of electrolyte the battery can hold determine the amount of energy the battery can store. However, the power density in flow-batteries depends on the rates of the electrode reactions occurring at the anode and cathode. A typical flow battery has been shown in Fig. 8. Some of the main characteristics of flow batteries are high power, long duration, and power rating and the energy rating are decoupled; electrolytes can be replaced easily [136].

6. Cost and efficiency trend of WT and wind energy

Currently, energy is one of the most intensely debated issues in the world. Studies show that the wind energy is an economically efficient and accessible energy resource for the large scale utilization in the near future and more remote future. Wind turbines do not use fuel and water, can be fully automated and need little time to commissioning. Their utilization makes it possible to save fossil fuel, decrease an adverse environmental effect, and in some cases proves to be economical. With good wind conditions (the average wind speed is above 7–8 m/s) the cost of electricity produced by medium and large sized WT can be 4–5 cents/kWh, and 2.5–3.0 cents/kWh in future [138,139].

The cost of wind energy is a function of the cost to build and operate a wind energy project and the amount of energy produced by the facility over its lifetime. From the 1980s to the early 2000s, average capital costs for wind energy projects declined markedly. In the United States, capital costs achieved their lowest level from roughly 2001 to 2004, approximately 65% below costs from the early 1980s [140]. In Denmark, capital costs followed a similar trend, achieving their lowest level in 2003, more than 55% below the levels seen in the early 1980s [141]. Over this time frame, technological innovations allowed for the development of larger turbines at lower costs. Economies of scale resulting from increased turbine size were followed by economies of scale in project size and manufacturing. More specifically, innovations in design, materials, process, and logistics helped to drive down system and components costs while facilitating turbine up-scaling. However, the initial period of capital cost reductions came to an end in the early to mid-2000s and the available data from the United States, Denmark, Spain, and

Europe show capital cost increases beginning around 2004 and continuing through at least 2007–2009. An array of factors, including raw material commodity prices and energy prices, has contributed to this increase in capital costs.

To maximize turbine performance, manufacturers have sought to develop more advanced turbine components and larger turbines. More advanced components promise greater efficiency, improved availability, and reduced generation losses [142,143]. A review of annual fleet-wide capacity factor data for the United States, Denmark, and Spain, spanning 1999 through 2010, demonstrates the resulting performance improvements, to some degree. Specially, data for the United States and Denmark demonstrate overall increases in average fleet-wide capacity factors on the order of 20% or more over this period (Fig. 9).

Significant reductions in capital cost and increases in performance between 1980 and 2003 had the combined effect of dramatically reducing the Levilized Cost of Energy (LCOE) of wind energy. Data from three different historical evaluations, including internal analysis by the Lawrence Berkley National Laboratory (LBNL), the National Renewable Energy Laboratory (NREL) as well as published estimates from Lemming et al. [144] and DEA [145], illustrate that the LCOE of wind power declined by a factor of more than three from more than \$150/MWh to approximately \$50/MWh over this period (Fig. 10).

7. Technological life cycle and obsolescence

Whenever a new technology is introduced into the market, its adaptation starts very slowly as it is usually expensive and unfamiliar to people. On the other hand, old technology is economical compared to the new one and well known and mature in the market. As the time goes on, new technology improves and finds more application and is generally recognized to be superior. Gradually, old technology loses its market share due to its inherent limitations and cannot keep pace with the new one. As a result of the rapid adaptation of the new technology and abandonment of the old technology, the penetration of the new technology reaches around 15% penetration level [146,147].

Since the pattern of the replacement of the old technology by the new technology is constant, the substitution process can be forecasted. Although the predicting methods are not absolutely perfect, it can follow a certain pattern [148–150]. Patent data are used to

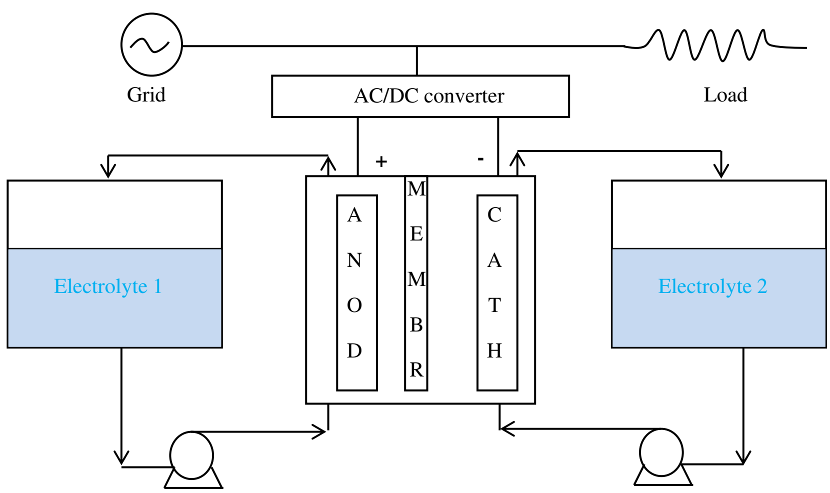

Fig. 8. Illustration of flow battery system [133,137].

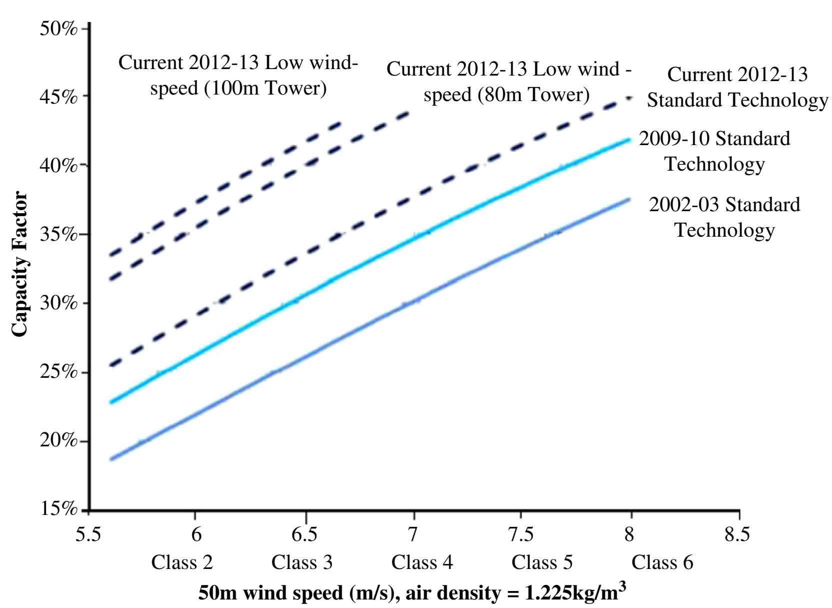

Fig. 9. Capacity factors increment relative to the historical technology [143].

analyze the technology trends and avoid the infringement. It has been found empirically that the cumulative patent applications over time follow a trend which resembles the S-shaped curve shown in Fig. 10 [151–153]. The S-curve is also known as the logistic curve that is used to evaluate the growth of technology at each stage in its life cycle and predict when a specific technology will reach a particular stage [151,152,154–156]. In the S-curve (Fig. 11), generally four different growth stages can be identified [154,157,158]:

(1) Emerging stage: in this stage the patent application is low.
(2) Growth stage: in this stage patent activity gradually increases.
(3) Maturity stage: from this stage patent application starts declining.
(4) Saturation stage: at this stage the technology approaches a natural limit.

After the saturation stage in the S-curve, the existing technology has reached its full potential and again the search for a new technology has started [150,153,156].

On the other hand, the actual obsolescence of technology started with the decline of the market share of technology. Initially, the replacement of old technology is very low, but gradually it matures and its deployment accelerates. Consequently, it begins to trigger the displacement of the older technology. Whenever a new technology reaches the rapid adaptation stage, the obsolescence of the technology accelerates. Then a new technology saturates the market, and its deployment slows and the rate of obsolescence of the old technology decreases. Finally, the market share of the old technology reaches zero, and the total obsolescence is achieved [159–166]. Fig. 12 shows the relationship between the adaptation of the new technology and obsolescence of the old one.

Table 5 shows the overview of the wind-energy technology development trend, challenges and solutions. It can be seen that some old technologies can be replaced by the new ones whereas some of them were not used previously but in the future these will be mandatory for sustaining wind power.

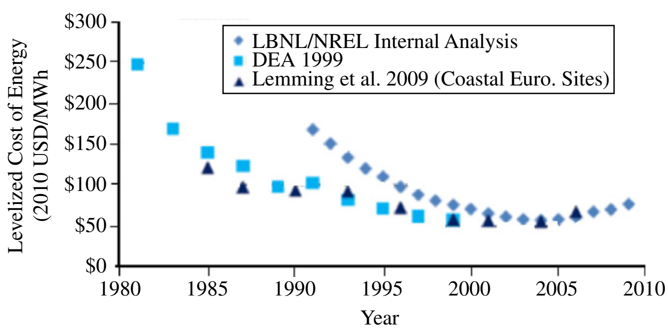

Fig. 10. LCOE for wind energy from 1980 to 2009 for the United States and Europe [144,145].

8. Conclusions

The significant outcomes of this study are given below:

- Among the top wind power countries, China has occupied the first position with the installed capacity of 62,733 MW at the end of 2011 and growth rate around 98% over the projection period 2005–2011. The global wind power capacity is 194.4 GW at the end of 2010 whereas in 1996, it was only 6.1 GW.
- Within the last three decades, the wind turbine size has been enlarged around 10–12 times while the unit capacity of wind turbine developed from 100 kW to 2 MW. It is expected that in the near future the wind turbine capacity can be increased up to 10–12 MW.
- In the 1980s and early 1990s, some attempts were made to commercialize one and two bladed wind turbines; however, in the modern time three bladed wind turbine has established itself as the most economical and effective one.
- Though the Horizontal Axis Wind Turbine (HAWT) is highly developed and used all over the world, the recent R&D has shown that the Vertical Axis Wind Turbine (VAWT) is more economical and efficient in respect of using land. Generally, to maintain 90% of the performance of isolated HAWTs, the turbines in a HAWT farm must be spaced 3–5 turbine diameters apart in the cross-wind direction and 6–10 turbine diameters apart in the downwind direction. In such cases, it is found that by using VAWT instead of HAWT on the same land area, it is possible to produce more than

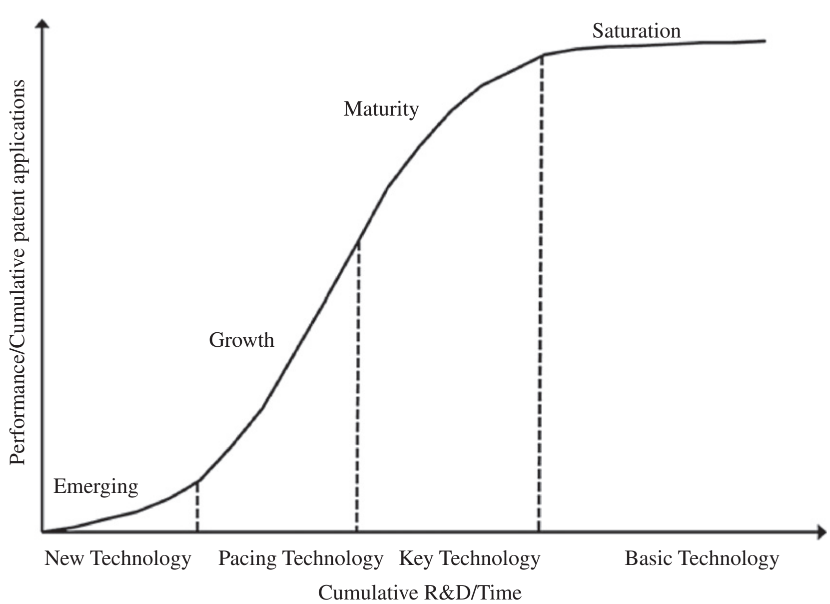

Fig. 11. A typical S-curve: the life cycle of the technology [157].

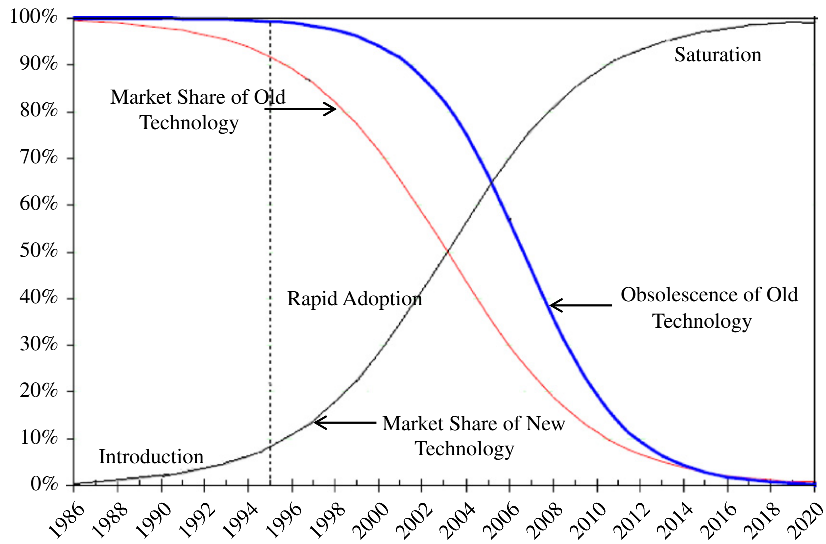

Fig. 12. Typical obsolescence chart of the technology [167].

Table 5
Development trend, potential challenges and solutions wind energy technologies.

Feature	Trend/Progress of the wind energy technologies
Wind turbine	Last 3–4 decades, the HAWTs dominated the wind turbine world. R&D continue on VAWTs in full phase as it is individually more effective than HAWT [45]
Turbine height	In 1980s the maximum height of a wind turbine was around 15 m but now it is around more than 250 m [87]
Turbine capacity	In 1980s and 1990s, the turbine capacity was 20–500 kW but now the capacity is around 2–5 MW [82]
Turbine blade	In 1980s, some attempt was taken to commercialize the one or two bladed turbine but now 3 bladed turbines are commercially available [68]
Power generation	By using the same space, VAWT is able to produce 10 times more wind energy than that of HAWT [114]
Power density	Power density for VAWT is 10–12 times more than that of HAWT
Land requirement	Less land is required for the VAWTs [114,168]
Energy storage system	Previously the energy storage system was not so much necessary but now it is mandatory for wind farm as the wind energy generation has been increase significantly [126,127]. The fuel cells and batteries are the two most impacting energy storage devices in RE systems
Space and efficiency	For wind energy, space is the much more demanding concern when it is considered HAWT, however, by using the VAWT and Fish Schooling Concept this problem can be solved out in the near future [114]

10 times of wind energy. Therefore, in the future VAWTs can be more appropriate replacement of HAWTs.

- Due to the stochastic nature of wind and to fill up the existing gap between availability and requirement of energy, the energy storage system is undoubtedly very much needed.
- The adoption of a new technology starts very slowly because its introduction is usually expensive, unfamiliar and imperfect. As the days pass away, the new technology becomes recognized as the superior one while the old technology becomes obsolete because of its inherent limitations.

Acknowledgment

The authors would like to acknowledge the HIR-MOHE project. The research has been carried out under the Project no. UM.C/HIR/MOHE/ENG/24.

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